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A possible signature for quark deconfinement in the compact star in 4U 1728-34

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Abstract. In a very recent paper Shaposhnikov *et al.* (2003) have extracted very tight constraints on the radius and the mass for the compact star in the low mass X-ray binary 4U 1728-34, from the analysis of a set of Type I X-ray bursts from this source. In the present letter, we perform a systematic comparison between the mass-radius (MR) relation given by Shaposhnikov *et al.*, with the theoretical determination of MR curves for compact stars using some of the most recent and realistic models for the equation of state for stellar dense matter. Our study clearly reveals that the semi-empirical MR relation for the compact star in 4U 1728-34 is not compatible with models of neutrons stars composed of nuclear matter or hyperonic matter, while it is consistent with strange stars or neutron stars with a core of deconfined quark matter (hybrid neutron stars).

Key words. neutron stars – equation of state – X-ray burst - low mass X-ray binaries

1. Introduction

An accurate measure of the radius and the mass of an individual "neutron star" will represent an extraordinary physical information to solve the long-standing puzzle on the internal constitution of these fascinating astrophysical bodies and to discriminate between different models for the equation of state (EOS) of dense hadronic matter.

In a very recent paper Shaposhnikov *et al.* (2003) (hereafter STH) have analyzed a set of 26 Type-I X-ray bursts for the low mass X-ray binary 4U 1728-34. The data were collected by the Proportional Counter Array on board of the Rossi X-ray Timing Explorer (RXTE) satellite. For the interpretation of these observational data Shaposhnikov *et al.* (2003) used a model of the X-ray burst spectral formation developed by Titarchuk (1994) and Shaposhnikov & Titarchuk (2002). Within this model, STH were able to extract very stringent constrain on the radius and the mass of the compact star in this bursting source.

In the present letter, we perform a systematic comparison between the MR relation given by STH with the theoretical determination of MR curves for compact stars. We have calculated the MR curves for non-rotating compact stars in general relativity using some of the most recent and realistic models for the equation of state for stellar dense matter. In particular, we consider the possibility that the compact star in 4U 1728-34 could have a core of deconfined quark matter (hybrid neutron star) or the possibility it could be a strange star.

2. Results

The radius and mass for 4U 1728-34, extracted by STH for different best-fits of the burst data, are depicted in Figure 1 by the filled circles. Each of the four MR points is relative to a different value of the distance to the source (d = 4.0, 4.25, 4.50, 4.75 kpc, for the fit which produces the smallest values of the mass, up to the one which gives the largest mass). The error bars on each point represent the error contour for 90% confidence level.

An additional restriction on the possible values of the radius and mass of the compact object in 4U 1728-34, has been derived by Li *et al.* (1999), using the transition layer model (Titarchuk & Osherovich 1999) to fit the observed Quasi Periodic Oscillations (QPOs) in the persistent emission of this source. The stellar radius R must be smaller than the inner radius R_0 for the accretion disk around 4U 1728-34, which is given by $R_0 = 9(M/M_\odot)^{1/3}$km (Titarchuk & Osherovich 1999, Li *et al.* 1999). In addition, R_0 must be larger than the radius R_{ms} of the last stable circular orbit around the star, plotted as a dotted curve in Figure 1 (Li *et al.* 1999). Therefore, according to Li *et al.* (1999) (see also Bombaci *et al.* 2000), the allowed range of the mass and radius for 4U 1728-34 is the region in the lower corner of the MR plane confined by the dashed curve ($R = R_0$) and by the dotted curve.

It is very encouraging to notice that the analysis of two very different astrophysical phenomena (QPOs and X-ray bursts) associated to this source, produces constraints on the radius and mass of the compact star which are consistent each other.

Next we consider the theoretical mass-radius curves calculated solving the stellar structure equations in general relativity for non-rotating stars and using a representative set for

some of the most recent and realistic models for the equation of state for dense stellar matter. The three curves labeled BBB1, BPAL32 and GM3, represent the MR relation for "conventional" neutron stars, *i.e.* for stars whose core is assumed to be composed by an uncharged mixture of neutrons, protons, electrons and muons in equilibrium with respect to the weak interaction. The curve BBB1 refers to the stellar calculations based on the microscopic EOS for β-stable nuclear matter computed by Baldo *et al.* (1997) using the Brueckner-Bethe-Goldstone many-body theory with realistic two-body plus three-body nuclear interaction. The curve BPAL32 shows the MR relation calculated with a phenomenological EOS for nuclear matter (Bombaci 1995, Prakash *et al.* 1997) derived by a density-dependent effective NN interaction. The curve GM3 is relative to a neutron star sequence calculated within a relativistic field theoretical approach in the mean field approximation (see *e.g.* Serot & Walecka 1986); here in particular, we used the GM3 parametrization (for the pure nucleonic case) given by Glendenning and Moszkowski (1991). Other realistic models for the EOS of nuclear matter, as for example the one of Wiringa *et al.* (1988) or that of Akmal *et al.* (1998), produce neutron stars with "large" radii between 10 – 13 km (in the mass range 0.8 $M_\odot$ – M_{max}).

The curve labeled Hyper depicts the MR relation for a neutron star in which hyperons are considered in addition to nucleons as hadronic constituents. Here we used the parameter set GM3 of reference (Glendenning and Moszkowski 1991). The MR curve labeled K^- is relative to neutron stars (Glendenning & Schaffner-Bielich 1999) with a Bose-Einstein condensate of negative kaons in their cores.

It is clearly seen in Figure 1 that none of the neutron star MR curves, for all the EOS models described so far, is consistent with the radius and the mass for 4U 1728-34 extracted by STH. Therefore 4U 1728-34 is not well described by an *hadronic star* model (*i.e.* a neutron star with a core made of different hadron species).

Next we consider the possibility the compact star in 4U 1728-34 is a *strange star*, *i.e.* a compact star consisting completely of a deconfined mixture of *up* (u), *down* (d) and *strange* (s) quarks (together with an appropriate number of electrons to guarantee electrical neutrality) satisfying the Bodmer–Witten hypothesis (Bodmer 1971, Witten 1984). The two curves labeled B70 and B85 in Figure 1 give the MR relation for strange stars described by an EOS for strange quark matter (Farhi & Jaffe 1984) based on the MIT bag model for hadrons. These two MR curves are obtained taking B = 70 MeV/fm^3, and B = 85 MeV/fm^3. In both cases the mass of the strange quark is m_s = 150 MeV, while *up* and *down* quarks are considered massless. The curve SS1 gives the MR relation for strange stars calculated with the EOS by Dey *et al.* (1998).

Finally, we consider the possibility the compact star in 4U 1728-34 is an *hybrid neutron star*, *i.e.* a compact star which possess a quark matter core either as a mixed phase of deconfined quarks and hadrons, or as a pure quark matter phase. In Figure 1, we plot the MR curves obtained for hybrid stars with the GM3 equation of state for the hadronic phase (case with hyperons) (Glendenning and Moszkowski 1991), and with the bag model EOS for the quark phase (Farhi & Jaffe 1984) taking B = 80 MeV/fm^3, m_s = 150 MeV, $m_u = m_d = 0$ (curve Hy1), or with B = 100 MeV/fm^3, $m_s = m_u = m_d = 0$ (curve Hy2).

Figure 1 clearly demonstrates that a strange star or an hybrid star model is more compatible with 4U 1728-34 than a neutron star one. Here we have considered a limited yet representative set for some of the most recent models for the equation of state for dense stellar matter. We have checked that other models for hybrid stars and strange stars are in agreement with the MR for 4U 1728-34 extracted by STH. This is particularly true, for example, for some of the hybrid star models discussed by Burgio *et al.* (2002) where a density dependence of the bag constant is introduced to describe the quark phase, or in the case of strange stars (Drago & Lavagno 2001) calculated within the Color Dielectric Model for strange quark matter.

3. Conclusions

Our study clearly reveals that the semi-empirical MR relation for the compact star in 4U 1728-34 obtained by STH is not compatible with models of neutrons stars with cores composed of nuclear matter or hyperonic matter (*hadronic stars*), while it is consistent with strange stars or neutron stars with a core of deconfined quark matter (hybrid neutron stars).

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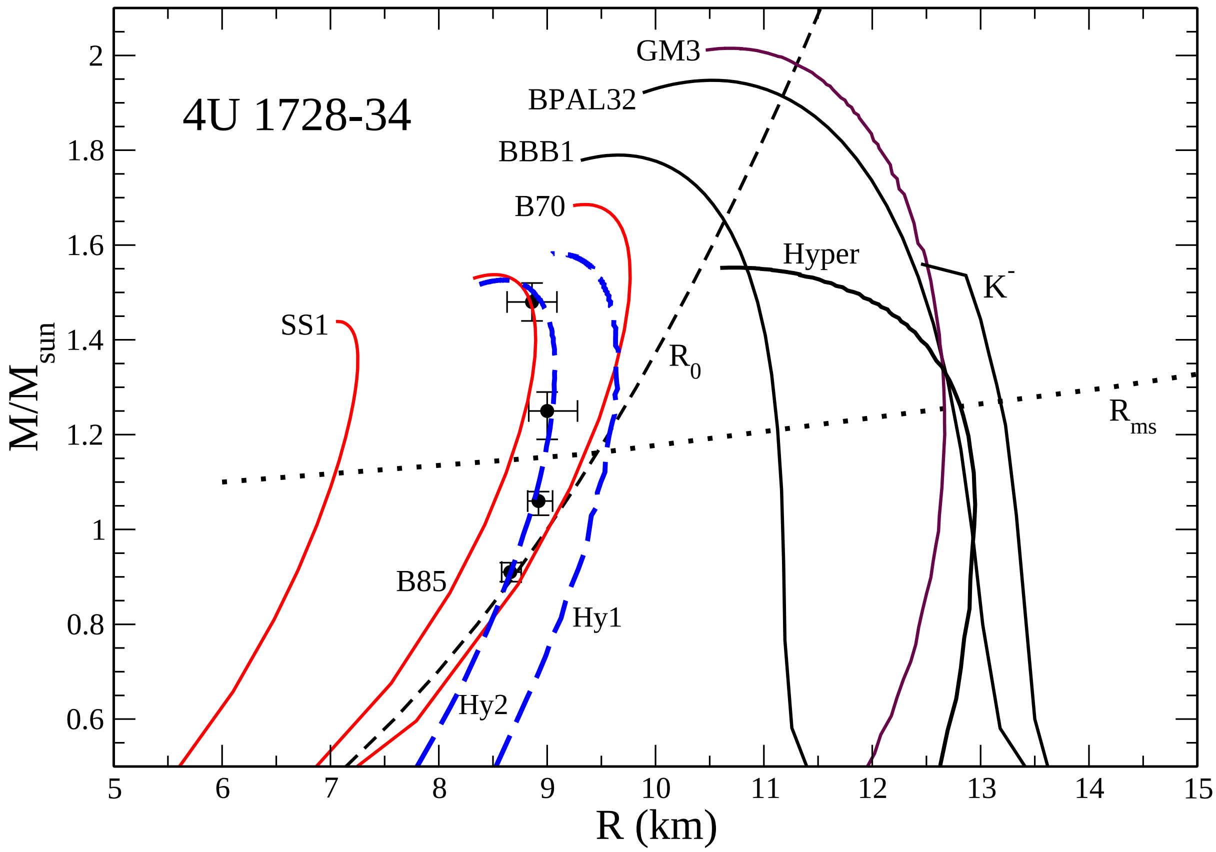

Fig. 1. The radius and mass for 4U 1728-34, extracted by Shaposhnikov *et al.* (2003) for different best-fits of the X-ray burst data, is shown by the filled circles. The error bars on each point represent the error contour for 90% confidence level. We show also the restrictions on the possible values of the radius and mass for 4U 1728-34 derived by Li *et al.* (1999) (region in the lower corner of the MR plane confined by the dashed curve ($R = R_0$) and by the dotted curve). The three curves labeled BBB1, BPAL32 and GM3, reprersent the MR relation for "conventional" neutron stars. The curve labeled Hyper shows the MR relation for a neutron star with an hyperonic core, and the curve labeled K^- is relative to neutron stars with kaon condensation. The two curves Hy1 and Hy2 give the MR relation for hybrid stars. Finally, the curves B70, B85, and SS1 are relative to strange stars.